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European Technology for Reducing Exhaust Pollution from Naval Ship Engines

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ABSTRACT

In response to the world-wide interest in reducing air pollution, the U.S. Navy is studying methods for lowering emissions from new, as well as existing, ship engines. As part of those studies, this report summarizes an examination of the science and technology base in Europe related to marine engine combustion and emissions. On-site visits in 1995 found a strong theoretical and bench-scale science capability, as well as considerable facilities for full-scale engine operation and diagnostics. Activities on the part of the owner/operator community were found to be diverse, with some aggressively pursuing low emission engines, while others were delaying action until the international regulatory situation clarified. It is concluded that the European science and technology base for the reduction of ship engine emissions is quite good, due in large part to prior work in support of European Community and national programs to reduce exhaust pollution from land vehicles and aircraft. The technology is believed to be adequate to provide realistic options for meeting forseeable international regulations on exhaust emissions from naval ships.

ADMINISTRATIVE INFORMATION

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PREFACE

In the early 1990's the California Air Resources Board (CARB) proposed a set of air emission regulations calling for reductions in NOx emissions from aircraft and ship engines up to a factor of 10. This challenge to the engine community caused an international flurry of R&D programs to search for ways to meet this goal for both diesels and gas turbines. These new investigations were superimposed on an already extensive technology base for central station and automotive applications. The present survey was proposed to assess the science and technology base that European NATO countries apply to ship engines, and to recommend areas where coordination with U.S. Navy science would be beneficial.

Contemporaneously with this survey, the CARB withdrew its proposed severe regulations and deferred the interstate transportation matter to the EPA, who in turn has coordinated the ship emission limits with the International Maritime Organization. The IMO, being more sensitive to the world-wide economics of ship operations, is currently considering a gradual introduction of low emission engine technology with the first step being a 30% reduction in NOx for new engines. Although the immediate requirement for greatly reducing NOx, and other pollutants, from ship engine exhausts has been postponed, the enabling technologies remain of interest to the U.S. and other Navies. A slower introduction of new regulations will allow all technologies more time to mature and will allow naval ship designers more time to select and develop those systems that best meet the military requirements. This report provides a snapshot of the European technology with regard to ship engine combustion and emission control as of 1995, and can be used a background for future decisions.

INTRODUCTION

The powering of naval ships and aircraft depends on the controlled combustion of air/fuel mixtures in both the diesel and gas turbine thermal cycles. Although many engines using these cycles have been developed empirically over the years, the details of their combustion processes are characteristically complex and difficult to describe on a theoretical basis. Furthermore, the interactions of the chemical, thermal and fluid phenomena that provide the basic heat addition in the engine frequently result in unwanted secondary effects. One such set of unwanted effects of growing importance is the appearance of atmospheric pollutants in the exhaust following the combustion of liquid hydrocarbon fuels. Compounds hazardous to human health such as CO, NOx, SOx, UHC, soot, PAH, etc., are found to appear in the exhaust in significant amounts. For example, in a modern ship diesel engine, the amount of NOx in the exhaust can be as much as 10% of the mass of fuel consumed, and the soot as much as 1%.[1] At this rate, a 1500 kW diesel generator on a typical naval ship might produce 100 tons of NOx per year. Unfortunately, it has been found experimentally that most engine modifications intended to reduce NOx also increase soot, as well as having an adverse effect on efficiency and/or power density.[2] Although the continuous combustion process for gas turbines appears to be quite different, the NOx production is only somewhat less severe.[3] For a modern gas turbine, as much as 3% of the mass of fuel consumed can appear as NOx in the exhaust. In this case, instead of soot, it is generally observed for gas turbines that CO levels increase undesirably as changes are made to reduce NOx.

Considering the various regional regulatory conditions that might impact ship activities, the international maritime and naval communities are working continually to identify acceptable and uniform limits on engine emissions.[4] Self-imposed rules limiting NOx from new ship diesel engines are currently being finalized by the International Maritime Organization (IMO) to which the Coast Guard represents the U.S. interests. The limits now being proposed call for NOx emissions to be based on energy output and engine rated speed, (Nd).

$$NOx \leq 45\ (Nd)^{-0.2}\ g/kWh \quad 130<Nd<2000\ rpm$$

For a typical new 1800 rpm diesel generator to be installed on a navy ship, the NOx limit would be 10 g/kWh or about 5% of the mass of fuel consumed. The related EPA proposal for U.S. waters calls for new marine diesels to produce less than 9.2 g/kWh, starting in the year 2000. These limits are associated with a weighted average of several measurements taken over an ISO test cycle centered on 70% of design power. Bigger, and lower speed, engines would be allowed proportionately more NOx under the IMO rule.,

It should be mentioned at this point that the U.S. EPA and land transportation diesel engine manufacturers have agreed to a NOx limit of 3.3 g/kWh for engines produced beyond 2004, and below 1.3 g/kWh as a long-term goal. For gas turbine engines, no maritime regulations are being proposed. In the early 1990's, the California Air Resources Board

(CARB) proposed that NOx emissions for new diesels be held below 1.5 g/kWh and below 0.8 g/kWh for new gas turbines, but this has since been withdrawn. Nevertheless, the threat of these low values has produced considerable R&D around the world to explore ways of meeting the levels proposed by CARB.

There currently exists a considerable body of technology related to the engineering aspects of reducing engine pollutants. It is believed that the proposed IMO diesel NOx limits will be achieved with this engineering knowledge. However, meeting marine engine goals that are more severe, similar to the land transportation limits, will require further understanding of pollutant formation and techniques for adjusting engine conditions so as to limit the discharge in the exhaust. With regard to all shipboard engines, the IMO plans to re-examine its rule every five years, such that lower limits may be expected in the future for at-sea applications.

Looking at the U.S. Navy situation,[5] only a few major ships are planned to be built in the next five years, e.g., follow-on DDG-51 Aegis Cruisers that are gas turbine powered, and the LPD-17 class amphibious ships using large diesels. Of course, there are now over 500 large gas turbines used for naval propulsion, and over 2700 diesels of various sizes on all types of ships. Considering the above, the current U.S. Navy approach with regard to engine emissions is:

- Build future ships with emission compliant engines
- Develop emission control techniques which meet unique Navy needs for existing high population high emitters
- Obtain waivers as needed for operations

Currently the Navy has R&D programs to demonstrate the practicality of water injection to reduce NOx in gas turbines and diesels, the feasibility of a diesel exhaust catalytic aftertreatment device, and, through ONR, the development of some basic science associated with pollutant formation and reduction under naval engine conditions. Before discussing European technology, the following section outlines some of the current theoretical and experimental understanding for engine exhaust pollution, so that the foreign activities can be placed in a context of current technology.

ENGINE THERMOCHEMISTRY OVERVIEW

Each engine type used for ship powering creates its own unique conditions under which combustion and pollutant formation occur. Design analyses of these chemical processes generally include the times, temperatures, pressures, materials, and geometries characteristic of each engine.[8,9] Fortunately, for NATO navies, the fuel is a standard one, NATO-F-76, a clear petroleum distillate . Some of its properties are given in Table 1, indicating that it has low flammability and good compression ignition qualities, especially as delivered to the ship. In both engine types this common liquid fuel is atomized into a fine spray and mixed prior to combustion with hot pressurized air in various amounts depending on power level. Both cycles operate with an overall stoichiometric excess of air, approximately 2 to 1 for the diesel and 3 to 1 for the gas turbine, at rated power.

For the reciprocating diesel cycle the combustion process occurs through compression ignition of the fuel spray in a repeating series of fundamentally unsteady events. The time scale of these events is closely regulated by engine speed. At 1800 rpm each 10 degrees of shaft rotation takes about 1 ms and all essential injection, combustion, and pollution formation events are complete in about 45 degrees of rotation, or less than 5 ms. Additionally, for the diesel cycle, compression ignition requires a high engine pressure ratio, and consequently high initial bulk and flame temperatures. Pressures at the start of the power stroke are in the range of 100 atm, while peak stoichiometric temperatures at flame fronts may reach 2500 K.[10]

In the gas turbine engine, fuel injection and combustion occur in a seemingly steady manner. The flame, once started, is stabilized by recirculating vortical fluid motions that continually return a portion of the hot combustion products to ignite the incoming air/fuel mixture.[11] In this case maximum compression pressures are of the order of 20 atm, and temperatures at the droplet/air flame fronts are therefore proportionately lower than for the diesel engine. The time available for reaction depends on volume flow rates and whether the fuel particle moves through the combustor in a plug flow or batch reactor mode, but might be 10 ms. or longer.

Interestingly, for any particular engine of either type, the mass of NOx produced per mass of fuel tends to be constant, varying little with power or speed. This behavior suggests a common combustion mechanism wherein each fuel droplet burns somewhat independently. Thus even at reduced powers, with lower cycle temperatures and pressures, fewer injected droplets simply produce proportionately less NOx.[10] Thus a commonly used measure of NOx production is the Emission Index, EI, expressed as gm NOx/Kg fuel.

Although the intended products of combustion are just CO_2 and H_2O, many other results are possible. At this time, the most important of the unwanted products are NOx, CO, and carbon particulates (soot). However, incompletely burned fuel and some of its thermally reformed intermediates may be important in the future. As stated previously, NOx is now the major pollutant of importance for marine engines. It is believed to be created at high temperatures through nitrogen oxidation pathways termed, the "prompt" and "Zeldovich" mechanisms.[12] The prompt chemical path involves CHN radicals and occurs primarily in fuel rich zones as part of the fundamental combustion reaction sequence. Reaction rates are fast, but only moderately dependent on temperature. The Zeldovich mechanism occurs through a path involving O and N free radicals, such that the reaction rates are slower, but considerably more temperature sensitive. The kinetics of the forward and reverse Zeldovich reactions allow NOx to be formed easily at hot spots, if oxygen and nitrogen are available, but then effectively "frozen" because of the slower rate of the reverse reaction, and the brief exposure times at the severe conditions.

The discharge of the other important pollutants, CO and soot, is associated primarily with insufficient combustion times at high and intermediate temperatures, but the mechanisms are different. Especially in the case of soot, the generation of precursors (e.g., ethylenes and acetylenes), their transformation into carbon agglomerates, and the subsequent particle oxidation rates, as they move through the engine cycle, are areas of great variability and empiricism.[13]

The course of the above thermo-chemical processes are strongly related to the reactant temperatures, concentrations, and unsteady fluid mechanics in the combustion volume.[14] Thus reliable prediction of the comparatively small amounts of unwanted emissions from large diesel and gas turbine engines is critically dependent upon an understanding of the primary combustion processes. Currently these simultaneous effects are approximated in computer simulations varying from 1-D to 3-D, and from steady to unsteady. The most sophisticated of the U.S. diesel simulation codes, KIVA, developed at Los Alamos, is being used by many manufacturers and improved by the engine research group at Wisconsin.[8] For gas turbine applications, many steady 2 and 3-D combustion simulation codes exist, such as FLUENT and PHOENIX. In all cases these codes simplify the turbulence, reaction mechanisms, heat transfer, etc. such that their results are useful mainly for trend analysis, rather than for design. Therefore in the U.S., as in Europe, engine testing has been found to be the only reliable way to define these second order pollution effects.[15] Unfortunately, the gaps in technique between the theoretical approaches and the engine operating groups are such that interchange of results and the advance of technology moves slowly.

By experimenting with real engines as "black box" chemical reactors, and measuring the products, it has been known for over 20 years that certain engine modifications will reduce specific pollutants. For diesel engines, lower NOx has been achieved by any of the following, alone, or in combinations:[2,16]

- Delaying the time of fuel injection
- Higher pressure fuel injection
- Fuel injection in programmed pulses
- Cooling of the inlet air change
- Varying the inlet air swirl
- Exhaust Gas Recirculation (EGR)
- Water injection

While variations in these parameters can reduce NOx, each also produces a penalty to the engine in terms of efficiency, complexity or cost. U.S. engine manufacturers are exploring most of these options in detail, as well as studying exhaust gas after-treatment, to reach the 2004 and long-term limits.[17]

For gas turbines, the options are also numerous, but somewhat less critical to the Navy since NOx levels for this engine are already close to, and generally below, IMO-proposed marine diesel limits. Since many naval gas turbines are derivatives of aircraft engines, the NOx reduction options tend to reflect that technology.[18] Typically the following are used singly, although some techniques can be combined:

- Lean-burn Pre-mixed Pre-vaporized (LPP) combustion
- Rich-burn Quick Quench Lean-burn (RQL)
- Partially pre-mixed Lean Direct Injection with a pilot flame (LDI)
- Multiannular staged combustion
- Water injection
- Catalytic combustion

Again, each of these options brings along certain disadvantages in combustion stability, complexity and/or impacts on other pollutants.[19] Through DOD, NASA and DOE support, developments are underway on each, and, as mentioned previously, the Navy is planning a demonstration of the at sea feasibility of water injection to reduce NOx in a marinized aircraft engine. Based on the above brief background in NOx thermochemistry for diesels and gas turbines, it it now appropriate to discuss the European approaches to this problem.

EUROPEAN CLEAN ENGINE SCIENCE & TECHNOLOGY -1995

This study was originated to obtain, in a short period of time, a representative sample of European science and technology related to the reduction of ship engine emissions. It was known at the start that certain integrated emission research programs had been organized by the European Community (EC) for automotive diesels (e.g. IDEAS)[6] and for aircraft gas turbines (e.g. BRITE). Other activities by the Royal Navy, Lloyd's Register, the University of Athens, and the large engine manufacturers, related specifically to ship engines, were known to exist, but their scope and depth was unclear.

In order to assess a representative range of European programs, this study was structured around pre-arranged on-site visits and personal discussions with experts in engine manufacturing, design, operations and research. To help assure that all important issues were covered, this study was accomplished in two parts, with an intermediate period for evaluation. For logistical convenience the first set of visits focused on the UK for the April-May period, while the second part concentrated on the Continent during September and October. The UK phase was conducted from the ONR office in London. Figure 1 illustrates geographically the sites visited. The assessments on the Continent were carried out from Bonn, with the locations covered in that phase shown in Figure 2.

After reviewing the information obtained, it was felt that the results also could be presented most effectively by organizing the material into data from the UK, and then from the Continent. In addition, because of the near-term importance of the diesel technology, it was considered appropriate to discuss that topic separately for each geographical area and to treat the gas turbine and basic combustion research information as a combined topic for each region. Therefore the results of this study, representing the interests and capabilities of over thirty organizations from eight countries, are presented using that structure. Although this quick-look sampled only a partial set of the total European technology base for large engine emissions, it includes many of the leading experts and organizations. The capabilities observed on-site, combined with the programs and comments of those visited, are believed to represent an accurate cross-section of the European science and technology base that is being, or could be, applied to the reduction of exhaust pollution from naval ship engines.

DIESEL S&T IN THE UK

Table 2 presents a list of the diesel technology institutions in the UK that were visited in this study. It includes the senior investigator, the thrust areas and the sponsors. A quick glance at Tables 3, 4 and 5 shows that a considerable amount of combustion visualization is being sponsored by the EC through the Integrated Diesel European Action (IDEA) program. This combined EC and industry program is supporting work on fuel spray motions, auto-ignition delay, flame propagation, pollutant formation, and computational techniques. Within the UK itself, it was found that the government supports basic combustion research through the Engineering and Physical Sciences Research Council (EPSRC). Finally, most universities also have research tasks supported by the engine manufacturers such as Perkins, Lucas, Ford, VW and Fiat. Through these industrial arrangements the scientific groups provide detailed and directly useful diagnostics of combustion processes in prototype single and multi-cylinder engines.

In order to provide practical advice, many of the diesel technology groups specialize in engine operations to obtain answers for specific problems. Perhaps the most well developed of these is Bath University which has several large modern engine test cells. These are fully instrumented and connected to computer data handling systems. In addition, Bath does developmental testing of other engine components such as turbochargers. On a smaller scale, Glascow Caledonian has created a Department of Energy and Environmental Technology which includes a full spectrum of engine design, construction, and test capabilities for coastal maritime applications. Professor Campbell at Glascow has recently completed a survey of diesel emissions and control technology options for the Royal Navy. The National Engineering Laboratory (NEL), located just outside of Glascow, provides a special capability for inlet and exhaust duct gas dynamics, as well as for total engine testing. In the event that engine internal modifications are not sufficient to meet NOx goals, AEA Technology at the Culham Lab is doing experimental work on a cold plasma process for reducing NOx via a ceramic matrix system in the engine exhaust. This particular after-treatment concept, also under investigation in the ONR program, is somewhat controversial, but experiments seem promising.

From the theoretical standpoint there is widespread interest in the post-injection behavior of the fuel spray. For example, Professor Winterbone at the University of Manchester Institute of Science and Technology (UMIST) has developed an elaborate system of high-speed photography, using the Bowditch transparent piston head with copper-vapor laser illumination, to visualize the fuel injection and combustion steps. At Loughborough, Professor Dent is studying fluid motions in the cylinder as they are affected by inlet valve geometry modifications. PIV studies of internal cylinder vortical flows, followed up with KIVA computations have been made. In addition, Loughborough is doing work in combustion-initiated cylinder acoustic waves, and in radiation heat transfer.

In central London, Imperial College, with a very broad thermo-fluids program, is also doing significant work on the behavior of sprays of various types. They prefer the time-averaging Phase Doppler Anemometer (PDA) technique for measuring pre-combustion droplet size and velocity. In the computational area, Professor Gosman at Imperial College is developing the 3-D unsteady SPEED/STAR code, with a projected LES turbulence capability and a flamelet library of probability density functions for the determination of local reaction rates. In addition, Professor Arcoumanis at Imperial College is engaged in laboratory tests of the steady and transient soot emission and removal mechanisms for multi-cylinder production engines. To complement this, Imperial is also doing considerable work on theoretical models of soot formation.

All of these university teams, agree that "temperature" is the most significant variable for NOx production, and that the theory is adequate. On the other hand soot modelling is still very much an empirical art. To improve the European technology transfer in soot modelling, Leeds University holds annually a course to review the latest knowledge.

On the commercial side, Ricardo Consultants in Shoreham-by-Sea has formed a subscription-type consortium composed of several manufacturers and the Royal Navy, which is known as the Large Engine Low Emission Consortium, (LELEC). Through this consortium Ricardo will generate proprietary emissions performance data using a 200 mm diameter single cylinder test engine. Paxman Diesels in Colchester is already developing a new 2 MW engine with high pressure fuel injection, combined with inter-cooling and after-cooling of the air charge to give low NOx and smoke. Paxman believes that on-engine modifications will allow NOx levels as low as 2.3 g/kWh. In another approach, Lloyd's Register, which serves commercial shipping, has organized an environmental engineering group. Mr. Carlton's group, located on the southern edge of London, has obtained, and published, considerable data on diesel engine emissions from commercial ships operating at sea.[1] In addition, Lloyd's Register has developed a commercial 1-D unsteady computer model of ship diesel engine performance, including prediction of the major exhaust pollutants (MERLIN). New Orleans University has purchased this code for use under the ONR/ARPA Shipbuilding Technology initiative.

To summarize the marine diesel situation, Lloyd's Register has measured the current exhaust emissions levels at 0.04 to 0.10 gm NOx per gm fuel. Ricardo is engaged in proprietary research to determine ways to reduce these levels to meet the forecast goals. The EC-sponsored automotive diesel program is providing a well-organized set of theoretical and experimental data for their higher speed parameter range. A full spectrum of laser techniques is in use to diagnose spray behavior, flame front propagation, and emission levels. One, two and three dimensional CFD codes indigenous to Europe exist for engine analysis, and are being used by their engine manufacturers.

At the start of this study it seemed also that the Royal Navy might be a significant factor for developing low emission marine diesel technology, but their role was unclear. Therefore, near the end of this phase, a discussion was held with Cdr. John Swainson, RN at MOD-N, Foxhill, Bath. It turned out that the RN was in fact sponsoring an organized set of tasks aimed at providing the technology for large reductions in emissions for shipboard diesel engines. These tasks ranged from ship design impacts to university studies. They included a full-scale demonstration of a urea-based selective catalytic reduction, SCR, system on the exhaust of a Paxman Valenta engine. This unit, about twice the size of the muffler, and packed with cored ceramic bricks, operated at Paxman in the fall of 1995. It reduced exhaust NOx by over 90%, at the design operating temperature, and may be demonstrated later at sea if needed to meet regulations. Thus, with fewer resources than the U.S. Navy, the RN has dedicated and focused its actions to lead the UK marine diesel community toward reduced emission engines. This RN initiative should be watched carefully, and possibly even joined through cooperative actions.

GAS TURBINE AND COMBUSTION S&T IN THE UK

Although the primary concern with regard to ship engine exhaust pollution is NOx from the diesel, this study also included certain gas turbine emission reduction technologies, as well as some basic combustion research of general interest. Table 3 lists the UK activities visited that fell into these two categories, including the senior investigator, the focus and the primary sponsors.

Within the UK, Rolls Royce is without doubt the dominant force in gas turbine engines for aircraft, marine and stationary uses. Equally important is the fact that Rolls is developing, in cooperation with Westinghouse, the U.S. Navy's Intercooled and Recuperated

(ICR) gas turbine. This engine uses turbomachinery components from the Rolls RB-211 series of aircraft engines, and, is expected to be the future standard international naval power plant in the 30,000 hp class. Interestingly, the combustor for this engine was not taken from the aircraft design. Instead, the Rolls Industrial and Marine group outside Coventry, developed for the ICR a set of can-type combustors that is larger overall than an aircraft combustor, and fires radially inward. Currently, prototypes of this engine use an arrangement of nine separate can units, without emission reduction technology, and are said to produce 4 g/kWh of NOx. Nevertheless, Rolls is developing a new swirl-stablized, staged, "low NOx" can combustor for use on later versions of the naval ICR engine. As mentioned earlier, NOx and CO must be traded off in gas turbine combustion, and Rolls argues that the ICR cycle provides favorable gas conditions within which to optimize. As a general rule they believe local temperatures must be kept under 1800 K to control NOx when excess oxygen is present.

Closely linked to Rolls Royce is Cranfield University, a select graduate-only school that is well-integrated into the UK aircraft programs. Although Cranfield does typical bench scale combustion research, their strength lies in the facilities for large scale experimentation, approaching the prototype level. For example, they can do combustor sector studies at rated temperature and pressure at flow rates up to 4 kg/sec in a blow-down rig. Professor Greenhalgh has developed excellent capabilities in the most modern laser diagnostic techniques, including LIF and CARS. While most of Cranfield's work is aircraft-related, they also did the initial development of the radial can combustor for the marine ICR engine. Current research at Cranfield involves swirl-stabilized prevaporized combustion diagnostics, soot formation at real turbine engine conditions, and some work on a low-emission catalytic combustor. Part of this experimental work is being done in conjunction with parallel theoretical combustion chemistry modelling by Heidelberg University. This cooperative venture is being supported by the EC as part of the European aircraft gas turbine research program called "BRITE".

Other research, oriented more toward industial gas turbines, is underway at Imperial College. Although some small can combustor experiments have been performed, the thrust here is toward CFD and high temperature chemistry models. The STAR-CD code is available for 3-D combustor simulations, and improvements, incorporating LES and flamelet reaction rate probability models are in development. From these studies, Professor Gosman concludes that Zeldovich NOx and soot are primarily the products of volume reactions, and as such, not well described by first-level reaction sheet flamelet theories.[20] In the laboratory, model industrial burners are being studied to define combustion limits, some under several atmospheres pressure, and using vitiated air. Finally, under ONR support, Professor Whitelaw of Imperial College is exploring, at atmospheric pressure, some ideas in active combustion control to achieve flame stability and reduce NOx. Figure 3a gives an impression of the experimental area. Oscillations of the air, fuel, or injected water, have been introduced to ducted pre-mixed flames simulating an industrial burner, a bluff-body stabilized burner, and a sector of an annular gas turbine combustor. Interestingly, the Rolls Royce I&M combustion group was not familiar with Prof. Whitelaw, nor of the work at Imperial College.

Turning to the broader area of basic combustion research, Professor Bray of Cambridge University is a leader in this field. A classical system under study there is the axi-symmetric opposed burner arrangement with turbulent inflow. To broaden the experimental conditions, a water mist is added to one side, and the fine droplets are tracked with laser illumination. Cambridge believes that it is crucial to understand the combustion process at the microscale, and therefore are developing a DNS level of analysis. Hopefully such experiments will also illustrate the beneficial effects of using water additon to control NOx, CO, and soot. In another view of turbulent combustion, Leeds University is studying the propagation of flame fronts in pre-mixed pressurized bomb experiments. In this apparatus, Figure 3b, three large mixer motors are used to create the initial turbulence levels. These experiments may in the future include liquid droplets in the mixture, and will provide data related to Professor Sheppard's basic interests in ignition delay. Although not currently involved in engine emissions work, the Institute of Sound and Vibration at Southamption University has several knowledgeable faculty who have contributed to the research in diesel pulsed injection and gas turbine catalytic combustion.

From the perspective of reducing engine emissions, these UK combustion research studies are valuable because they illustrate many of the first order phenomena that precede pollutant formation. However, it is difficult to translate these research results into operating engine effects without considerable intermediate engineering analysis and parallel experiments on real engines. Nevertheless, this survey has shown that the UK has a broad base of science and technology that can be, or is being, used to develop large, low emission naval engines.

DIESEL S&T ON THE CONTINENT

Table 4 lists the diesel science and technology groups visited on the Continent, the thrust of each, the senior investigators, and some of their sponsors. Typically these groups were involved with the IDEAS program, and performed related work supported by the engine manufacturers, the national science agency of each country, and/or focused research societies (e.g. FVV-Forschungs Vereinigung Verbrennungs-kraftmaschinen or the DFG - Deutsche Forschungs Gemeinschaft). A glance at Table 4 indicates a local concern for soot production for land transportation engines, and an emphasis on NOx reduction for larger engines.

Considering the broad topic of engine systems research, the National Technical University of Athens is concentrating on the dynamic simulation of diesel engines in the ship propulsion application. Add-on models of NOx formation have been prepared to predict emissions from two and four stroke engines during steady operation and maneuvering transients. Recently Professor Kyrtatos was funded by NATO to host two workshops for the European Shipping Community discussing engine emission control and new ship propulsion technology. Currently, work on emissions is tapering off at Athens.

Supporting European diesel manufacturers are a number of indigenous design and consulting companies that work on a proprietary basis. One such company, AVL, located in Graz, Austria was visited. It employs 350 people in commerical engine development testing, and in research. At Graz, AVL operates a dozen test cells for small to medium sized engines, performs initial engine designs, and constructs prototypes. In order to offer a total engine combustion simulation package, AVL has also developed its own commercial CFD code, FIRE, which includes fluid mechanics and chemistry. In providing scientific support for its programs, AVL has investigated the burning behavior of liquid fuel sprayed into quiescent air at 900°K and 40 atm. PDA has been used to track droplets, the two color method to measure local temperatures, and a laser light scattering technique to measure soot concentrations. AVL believes that current European and U.S. automotive diesel emission goals will probably be met with incylinder modifications, and without high pressure fuel injection.

A second unique university-based automotive consulting organization exists at the RhineWestphalia Technical Hochschule (RWTH) in Aachen, Germany. This group is part of the Lehrstuhl fur Angewandte (Applied) Thermodynamik, LAT, and employs 120 persons to operate 20 engine test cells and four combustion reseach labs. Under the direction of Professor Pischinger, LAT also coordinates a Center for Automotive R&D that integrates the work of 15 other institutes at RWTH. LAT itself has specialized recently in research on soot formation following fuel injection into quiescent air at engine temperatures and pressures using the laser light extinction method. Interestingly LAT does no CFD. This computationally intensive work, along with additional proprietary engine testing, is done by an adjacent 300 person company in Aachen, FEV Motoren-technik, also managed by Professor Pischinger.

Of special mention at RWTH is the smaller Institute fur Technische Mechanik headed by Professor Norbert Peters. This institute is concerned with the scientific aspects of engine combustion, including the integration of chemical reaction models, flamelet techniques and CFD (e.g. KIVA). Some engine work is also done in this institute, but mainly for the purpose of combustion research. Cylinder variables such as fluid velocities, ignition locations, and flame propagation have been measured using copper-vapor laser illumination with the Bowditch quartzwindow topped piston. With almost 20 Ph.D. candidates, this institute is well-known for its contributions to the scientific literature. Currently the research is focusing on the principle that the impulse of the fuel spray is the primary factor that governs much of the subsequent combustion behavior in a diesel engine. Figure 4a illustrates the attention given to diesel technology at RWTH, while Figure 4b shows Professor Peters in his laboratory.

At the University of Naples, engine combustion research is done in cooperation with the nearby Italian National Research Council, CNR, Institutes of Combustion and of Motors. These institutes are concerned with mathematical modelling and real engine operational tests, while the Chemical Engineering Department of the university explores experimentally the details of soot formation and oxidation. The university research is based on fuel injection into the ubiquitous 900K, 40 atm quiescent air chamber with quartz windows. Soot and its precursors are studied using rapid chemical sampling as well as laser-induced incandescence of the particles.

One of the world's most modern and successful manufacturers of ship engines, Wartsila Diesel of Vaasa, Finland was visited to assess how they have approached the issue of emission control. Equally important was the possibility that the U.S. Navy may select four of their 9,000 hp Vaasa series engines on the new LPD-17 class ship. The R&D laboratory, just below the Arctic Circle, was found to be a major new 150 employee facility built around four large computer-controlled test cells for engine development. The Wartsila marketing goal is to offer an inventory of engine options that meet or exceed the pollution standards that ship owner/operators will encounter. Their R&D strategy is to accomplish this by developing the basic engine for higher compression ratios, e.g., 14, 16 or higher, and to design for delayed fuel injection so as to burn later, and cooler, with no efficiency penalty. In these designs, peak pressures will be over 200 bar. Thus Wartsila is sponsoring research at Turku and Trondheim Universities to study NOx kinetics for such conditions. In the design process this information is used in codes such as KIVA and WAVE (Ricardo) to simulate pollutant formation during spray combustion. For the medium speed naval engine, soot is not seen as a problem due to the longer time available for particle oxidation. For greater NOx reductions, Wartsila has available a separate water injection system for the 46 series engine. This system introduces water 20° before the fuel, cooling the gas, and thereby reducing NOx by 50% with no fuel penalty. Currently, a combined fuel/water injector is under development for which the water can be turned off when the ship is beyond local regulatory zones. For the ultimate in pollution reduction, Wartsila also has sea-going experience with the selective catalytic reduction, SCR, aftertreatment system using urea to reduce any remaining NOx. In summary, this manufacturer has acquired a broad technology base for emission reduction, with back-up scientific support, such that a wide range of NOx regulations can be accommodated with the newer engines.

To summarize, the scientific and developmental aspects of clean diesel engines are being pursued actively on the Continent. Engine manufacturers were found to use independent consulting/design groups, including universities, to explore new concepts. Such groups provide a considerable amount of engine-specific experimental data that can be applied quickly to the design of new engines. For the smaller engines, the major scientific interest was focused on soot, with a variety of laser techniques being used to study its behavior during the combustion of pulsed fuel sprays. For larger engines, the chemical kinetics of NOx formation, and methods to reduce this pollutant were of most concern.

GAS TURBINE AND COMBUSTION S&T ON THE CONTINENT

Table 5 lists the groups visited on the Continent that work on the topics of gas turbine applications or general combustion research. Of particular interest is the BRITE (Basic Research for International Technical Exchange) program supported by the EC and involving several universities in the UK as well as on the Continent. This program is focused on developing the basic chemistry and fluid mechanics for predicting NOx and CO production in staged gas turbine combustors. In contrast to the diesel area, this assessment found much less evidence of gas turbine manufacturers independently supporting academic work in combustion. Instead, within each country the national research agencies provided general support for steady combustion science.

The visit to the University of Zaragoza, Spain, provided some of the details for the EC-sponsored BRITE program aimed at creating an improved science base for low NOx and CO emissions from gas turbines. This three year study, being coordinated by Professor DoPazo, involves linked theoretical, experimental and computational activities at the Universities of Zaragoza, Heidelberg, Cranfield, Rouen, and Imperical College. The proprietary results will be monitored by Rolls Royce, SNECMA, MTU, BMW and Volvo to assure industrial usefulness. In addition to this EC program, the combustion team of six Ph.D. engineers performs a range of applied research for electric utilities, and for the Spanish National Research organization, CNRS, which maintains a coal laboratory on the expanding Zaragoza campus. Building on a capability in basic fluid mechanics, this group has completed research in vortex sheet mixing, spray generation, two phase jet flow, and combustion CFD. Current basic studies involve droplet mixing in shear layers, and the investigation of liquid mixing in screen generated turbulence using pdf, LES, and DNS computations to compare with experiments.

Combustion chemistry models for the BRITE program are being formulated by the Interdisciplinary Center for Scientific Computing (IWR) at the University of Heidelberg. This 30 member scientific staff specializes in isolating mathematically reduced-order reaction mechanisms from the hundreds of identified molecular and free radical combinations in combustion systems. For the computation of engine parameters, and emissions, this group prefers to describe the effects of flow and turbulence through the pdf method. In commenting on the beneficial effect of water for NOx reduction, Professor Warnatz noted that the high efficiency of the H_2O molecule in three-body dissociation reactions could be as important a factor as the thermal effect.

Another participant in the BRITE program that was visited in this survey is the Complex for Interdisciplinary Research in Aerothermochemistry (CORIA) at the University of Rouen, France. Professor R. Borghi, a leading theoretician in single and two phase turbulent combustion, is associated with CORIA as an advisor and lead investigator. This 100 person center is strong in experimental studies of combustion, flame chemistry and plasmas. Techniques such as LDV, PIV, LIF, Tomography, and fine-wire thermocouples are all used to study pre-mixed and spray combustion processes. CORIA has facilities to investigate unsteady fluid mechanics, air-assisted atomization, turbulent diffusion, and flow instabilities. Laser tomographic measurements of the propagation of flame fronts from natural gas injected impulsively into hot air are currently being used to gain further insight into flamelet modelling. In total, an extensive scientific capability for research into the fluid mechanics of combustion for gas turbine, and diesel, applications exists at Rouen.

At the other end of the technology spectrum is the ship operator, represented by the French Navy's Direction Construction Navales (DCN) headquartered in Paris. The Head of the Propulsion Department in DCN sits on NATO SWG-12, which handles all ship environmental issues, and is also the point-of-contact for the French involvement in the US/UK ICR program. (As part of the expanded ICR program, Rolls Royce is to provide DCN with the first prototype low emission engine, which will then undergo testing at their INDRET laboratory.) At this point the French Navy has no engine emission reduction program beyond the ICR evaluation. As a ship owner/operator, their strategy is to wait until the international regulatory rules on emissions become firm. At that time the DCN plans to gather data on their existing ship engines, and then assess what technology options will be needed for compliance. Thus, the French Navy is presently interested only in learning of the experiences of others as background for future decisions.

Two groups found to be working in the broader area of engine combustion science were at the University of Erlangen and the Technical University of Munich. The Chemical Engineering Department at Erlangen includes the 65-person Lehrstuhl fur Stromungs Mechanik (LSTM). This fluid mechanics research group is lead by Professor F. Durst, who has contributed significantly to the science of spray formation and droplet behavior. The institute is currently examining new PDA techniques for tracking sprays from multi-hole injectors, exploring a device for instantaneous flow measurement under pulsing pressure gradients, and a pursuing unique combustion process using porous media for flame stabilization. Although the latter concept is not being proposed for engine application, its emission performance is providing some special data under closely regulated burning conditions.

The Institute for Thermodynamics at the Technical University of Munich occupies a special place in engineering science due to the traditions of former Professors Nusselt and

Schmidt. The current combustion work is focusing on the hydrogen-air system. Applications range from reactor safety issues involving the propagation of pre-mixed flames through simulated building passageways to supersonic mixing and combustion for space vehicle propulsion. One particularly interesting project at Munich is the measurement of the compression ignition behavior of hydrogen-air mixtures under conditions simulating a large diameter diesel cylinder. This research, just beginning, has been motivated by an interest in transporting liquid hydrogen by ship, using the boil-off gas for propulsion. Although of no immediate interest for naval applications, this study could provide additional discrimination between models for prompt and thermal NOx because of the absence of the prompt NOx precursors in hydrogen/air combustion.

To review, the research into continuous combustion observed on the Continent (mainly BRITE) is organized so as to consider separately the mixing aspects of unsteady fluid motions, and the chemical kinetics of the complex set of reacting species. These phenomena are then combined and tested using a set of computational simulations, along with laser diagnostic experiments, to identify mechanisms for predicting and controlling emissions from gas turbine combustors. In addition to research for current engines, other thermal reaction processes such as burning in porous media and hydrogen/air combustion are being actively pursued. From the practical standpoint of the naval ship operator, the attitude of the French Navy with regard to engine emissions was found to be one of waiting until IMO agrees on a plan for regulation before starting any independent R&D or ship modification studies.

SUMMARY AND CONCLUSIONS

For U.S., and European, naval ships the most significant air pollution problem to be addressed by today's science and technology base is the reduction of NOx emissions from large diesel and gas turbine engines. The combination of nitrogen-oxygen thermochemistry with the combustion parameters of the diesel and gas turbine cycles has resulted typically in 10% and 3% respectively of the mass of fuel appearing as NOx in the exhaust. These rates produce considerable amounts of NOx, as well as other pollutants, which can be of concern in environmentally sensitive areas.

The IMO is currently considering a 30% reduction in NOx, from the existing marine diesel baseline, as a realistic first international regulatory step. If both ship engine types are treated equally, as now seems likely, the emissions from new diesels will be reduced significantly before gas turbines become affected by the regulations. This study reports on the science and technology in Europe that could contribute to meeting a range of potential emission regulations for both engines. The information obtained should be of special interest to the U.S. Navy because of the current and potential European engines in its inventory.

In Europe there now exist considerable differences in regard to the importance of the ship air pollution question and how it should be addressed. At the time of this assessment, the Royal Navy was found to be pro-active in encouraging the rapid development of ship technologies for achieving large reductions in diesel NOx. Alternatively, the French Navy was found to be moving slowly until the impacts of the IMO regulations become clear. A recent study of commercial ships by Lloyd's Register has characterized the European problem through at-sea measurements of emissions and computations of the resulting atmospheric effects. However, their reports only present data and do not recommend actions. In light of the current uncertainties, the European diesel and gas turbine manufacturers are positioning themselves to offer a range of options for low emission engines. In some cases the environmental technology for the marine engine is similar to that used on the equivalent land-based version, while for others the ship approach is different. And, of course, military ships have additional special requirements.

Considering first the status of engine technology, this study found that the European diesel manufacturers tend to develop new designs using established links with the science community. As a consequence, manufacturers, consultants, and universities currently have extensive empirical data bases from years of testing on small and large engines for land applications. Thus there is a considerable body of knowledge concerning how design parameters effect NOx, even though the details of the complex interacting mechanisms may be unclear. Diesel companies such as Wartsila and Paxman now believe that NOx reductions up to a factor of three can be achieved by traditional engine improvements such as higher compression ratios, fuel injection timing and shaping, air pre-cooling, etc. In addition, water injection is known to provide another factor of two reduction and SCR aftertreatments have been demonstrated that remove over 90% of the current NOx levels. To focus this technology on the marine issue, the Royal Navy has encouraged Ricardo to form the LELEC consortium to provide emission data specific to large medium speed engines. Although exhaust gas recirculation is a technique included in most European data bases, it was not found to be considered as a viable option for ship diesel engines.

The marine gas turbine technology base in Europe is centered on Rolls Royce, and their current major development is the joint US/UK 30,000 hp ICR engine. This naval propulsion engine uses turbomachinery from the RB-211 series aircraft engines, mated to intercooler, recuperator and combustor components designed specially for sea, and land, applications. A multi-can configuration was chosen early on for the combustor since it fit easily into the new flowpath, and initial developments were performed at Cranfield. Currently, Rolls Royce is testing an advanced swirl-stabilized and staged version of this combustor that is expected to produce even less NOx than CARB had proposed. Interestingly, this and other European gas turbine combustion hardware developments, were not found to be linked as widely with academia as was true for diesel components. The more theoretical devices studied by universities, such as porous or catalytic combustors, were not found to be of interest to the manufacturers.

Turning to the underlying European science base for clean engine combustion, it was clear from this study that past incentives for research came primarily from land applications. Fortunately, the considerable amount of prototype testing noted above has provided a phenomonologically rich data base that academia is organizing and expanding. Consequently, a large amount of research is underway to clarify the details of fuel injection, droplet evaporation, ignition, chemical kinetics, local NOx, soot, etc., all in the presence of turbulent fluid motions and mixing. As a result, a number of increasingly complex European engine combustion simulation programs are being used to compute how these phenomena interact. Codes such as MERLIN, STAR, WAVE, and FIRE, along with modified versions of the U.S. KIVA code, are all being applied to the engine exhaust pollution problem. Parallel experiments using laser illumination of combustion propagation in operating engines by UMIST and RWTH are providing flame and soot structures to validate the theory. Furthermore, a number of universities, exemplified by Cranfield and Rouen, are applying a range of advanced laser diagnostics to isolate specific combustion details. A recurring laser illuminated experiment for studying the production and oxidation of soot was fuel injection into a small quartz windowed chamber of hot, pressurized, quiescent air. The fundamental chemical kinetics equations for these multi-component combustion reactions are being defined and simplified at Heidelberg, while Imperial College and Leeds are focusing on more automotively useful soot kinetics models. Much of this research work was found to have been sponsored by the European Community as part of the IDEAS project, which has advanced considerably the science base for automotive diesels.

An important thrust by the European Community to expand the scientific base for clean aircraft engines is the BRITE program, coordinated through Zaragoza. This research, focusing on NOx and CO production in aircraft combustors, involves, many of the same universities in the UK and on the Continent that have worked in diesel science. It is planned to integrate computational techniques for fluid motions and mixing, chemical kinetics, and heat transfer for the case of "steady" combustion in an annular geometry. The program is structured to link the interests of the aircraft engine combustion technology community to academia through periodic meetings with a guiding consortia of manufacturers.

In conclusion, maritime regulations limiting NOx emissions from ships will soon be established by the EPA and IMO, and will impact diesel engines first. The European capacity for understanding, designing, and producing marine diesel and gas turbine engines meeting the projected requirements for low emissions was found to be quite good. Much of this technology exists today in hardware, due in large part to past developments for land applications. In addition, the supporting science base is continuing to grow through focused programs funded by engine manufacturers, the individual countries, and by the European Community.

RECOMMENDATIONS

Looking ahead, the U.S. Navy can expect to be offered a continuing series of European marine diesel and gas turbine engines with greatly reduced exhaust emissions. Engineering knowledge should be sufficient to select those technology combinations that integrate well into each new ship and mission. It is hoped that this report provides a timely indication of the European technology options that will be applied to naval engines.

Much of the ship-related engine emission technology seen in Europe is well-known in the U.S., and only selected testing is needed to evaluate it. However, there are also a few areas where European experience could contribute to a better U.S. Navy scientific understanding of engine combustion phenomena. It is therefore, recommended that Navy clean engine science programs be coordinated with the following work in Europe:

a.) Experience in adapting the U.S. KIVA code to the simulation of combustion in large engines, especially with regard to water addition,

b.) Research into mathematical techniques for obtaining accurate reduced order chemical kinetic models of combustion species,

c.) Special laser techniques for diagnosing pollutant behavior during fuel droplet combustion in engine conditions, and

d.) Understanding of plasma mechanisms for reducing NO in oxidizing atmospheres.

In order to transfer information in these topics effectively, it is believed that working relationships will be necessary between U.S. and European scientists. Because of potential proprietary issues, it may also be anticipated that special arrangements will be needed with the sponsors involved.

These Conclusions and Recommendations have been condensed from visits and discussions with just over 30 European science or technology groups knowledgeable in clean engine issues. Although the sample was small, the individuals included in this assessment were among the leaders in their fields. It is hoped that the views reported herein will be useful in appreciating and assessing those elements of the European science and technology base that can contribute to U.S. Navy interests in clean ship engines.

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BIOGRAPHY

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Figure 1. Engine Emission Science and Technology Groups visited in the UK.

Figure 2. Engine Emission Science and Technology Groups visited on the Continent.

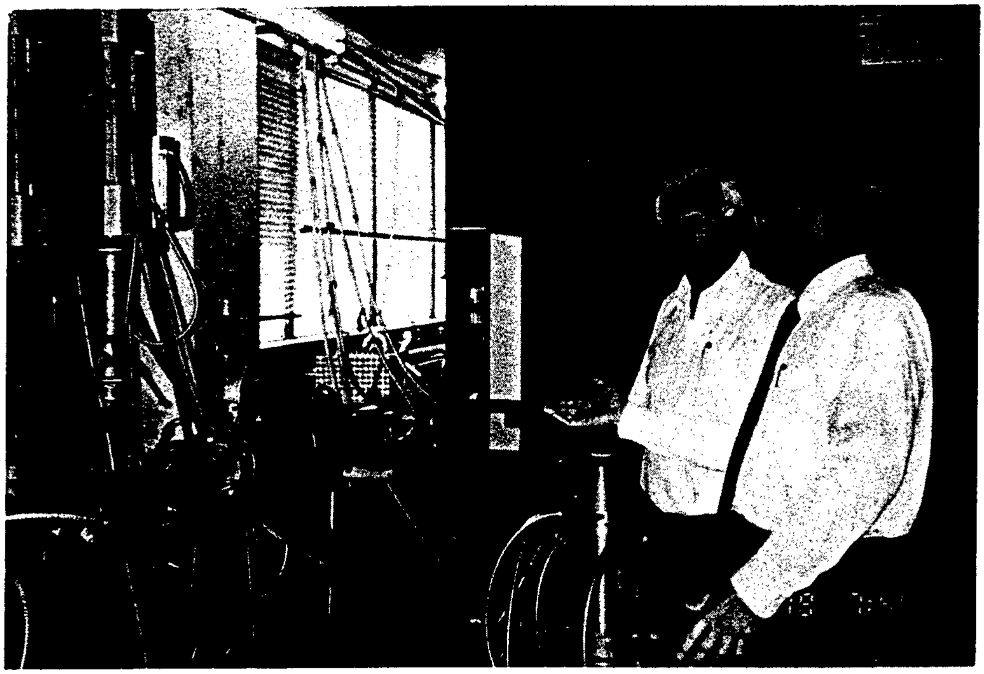

Figure 3a. The author in the combustion laboratory at Imperial College with Professor Whitelaw.

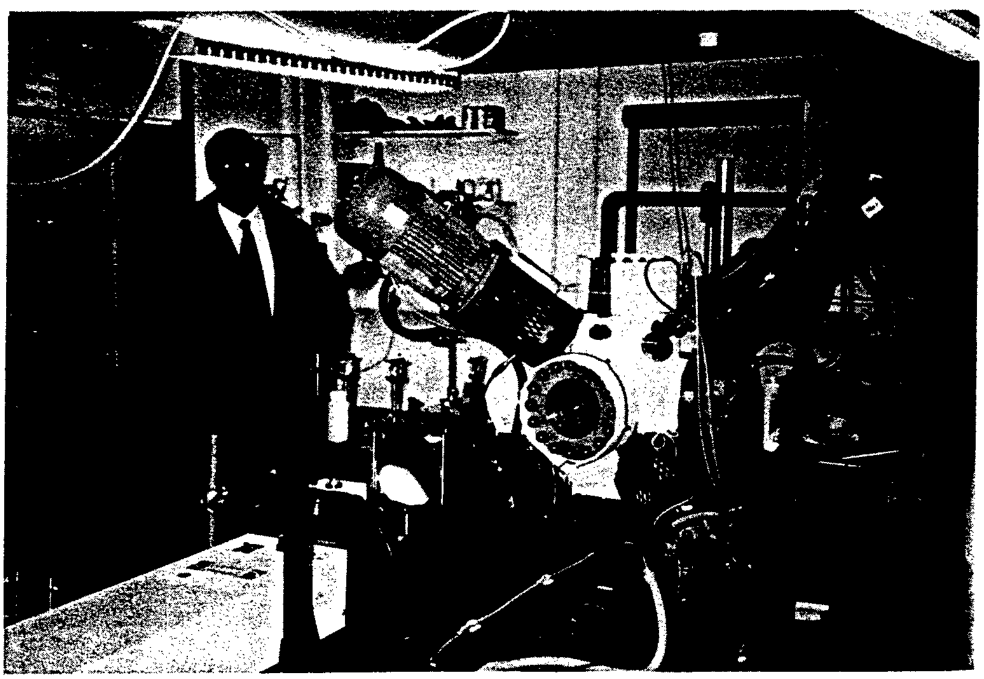

Figure 3b. Professor C.K.W. Sheppard in the laboratory at Leeds University with the stirred combustion bomb apparatus.

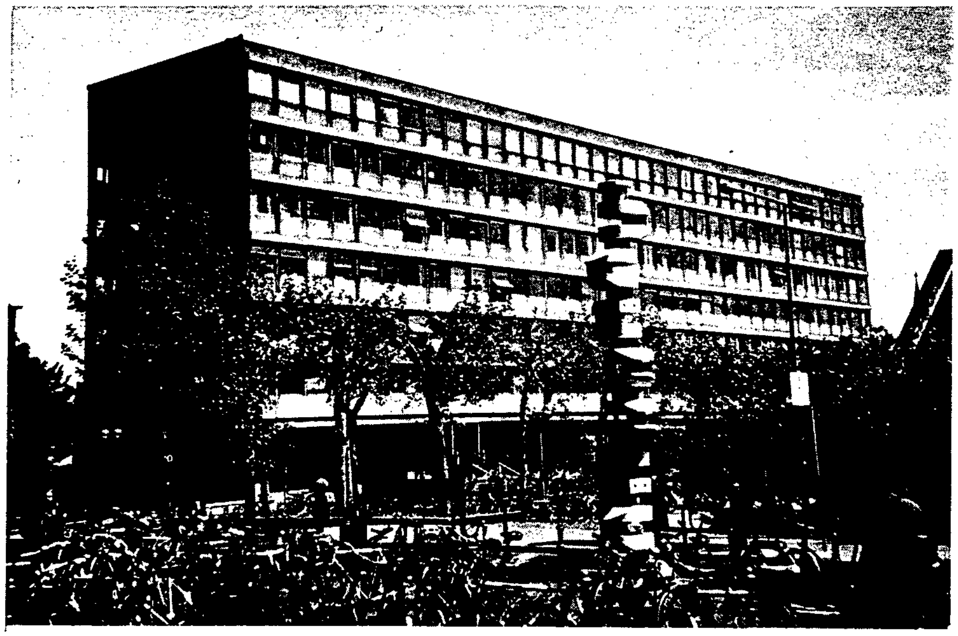

Figure 4a. View of RWTH campus in Aachen, Germany with diesel crankshaft symbol for the Technical School.

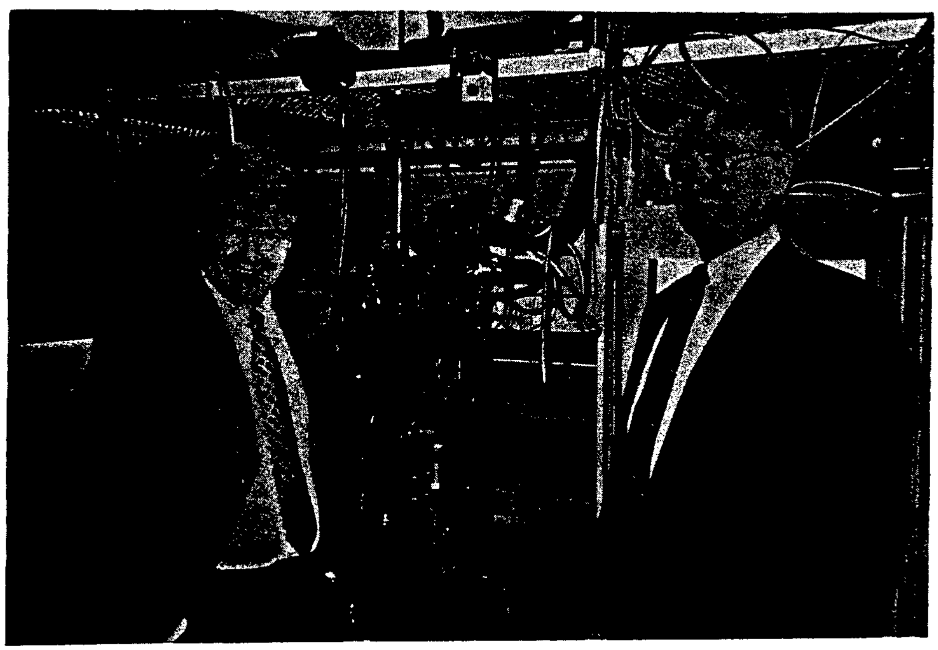

Figure 4b. Professor Norbert Peters in the Mechanics Laboratory of RWTH with the author.

Table 1. Comparison Of Selected Fuel Properties.

	Fuel Identification			
	Specification Values			As Delivered
Property	Jet A	No. 2D	NATO F-76	NATO F-76
Cetane No., C. Min	-	40	45	45
Flash Point, C, Min	38	52	60	81-87
Distillation, C				
90%, Max	-	338	357	335
End Point, Max	300	-	358	365
Viscosity, cSt (40C)	8*	3.0±1.0	3.0±1.3	3.4
Pour Point, C, Max	-	-	-6	-11
Freezing Point, C, Max	-40	-	-	-
Density, kg/m3	810	-	-	850

* Measure at -20 C

Table 2. UK Diesel S&T, Diesel Investigators, Thrusts And Sponsors.

GROUP	THRUST	INVESTIGATOR	SPONSOR
Bath	Engine test facilities, Turbos, 2 Cycle work	M. Owens S. Macgregor	Ford EPSRC
Glascow	Big engine design construction and test, and MOD-N diesel emission study	T. Campbell	EEC AutoRacers
Imperial	Droplet spray and combustion, transient soot production, and CFD modelling	J. Whitelaw C. Arcoumanis D. Gosman	Perkins Honda IDEAS EPSRC
Loughborough	Combustion acoustics, KIVA, swirl PIV, and radiation heat transfer	J. Dent	Rover EPSRC
UMIST	High speed films of combustion using CV laser, and large engine operation	D. Winterbone	Lucas EPSRC
Southampton (ISVR)	Pulsed fuel injection, and catalytic combustion	N. Lalor	Lucas? EPSRC?
AEA Technology	Catalysts for NOx, CO, UHC, and plasma for soot/NOx reactions	D. Raybone M. Davies	UK-DTI UK-MOD
Lloyd's	Environmental engineering, emission monitoring, MERLIN	J. Carlton Z. Bazari	Ford CommFlt
NEL	let-Exhaust gas dynamics, engine cooling, and EMMA	J. Bingham	UK-Govt
Ricardo	LELEC using 200mm Atlas engine, environment and acoustics focus	J. Niven	Private Consort
UK-MOD-N	Demonstrate urea SCR with Paxman, AEA plasma option, LELEC, and ship impact	J. Swainson	UK-Govt

Table 3. UK Gas Turbine and Combustion S&T, Investigators, Thrusts and Sponsors.

GROUP	THRUST	INVESTIGATOR	SPONSOR
Cambridge	Counter flow burner with water droplets, ignition delay, and DNS	K. Bray	EEC IDEAS
Cranfield	Laser Techniques, swirl mixing, soot, 10 atm. blowdown, Collaboration tasks	P. Hutchinson D. Greenhalgh	RR BRITE
Imperial	CFD with LES, chemical kinetics, soot, drops, pressurized burner active combustion control	J. Whitelaw F. Lockwood P. Lindstedt W. Jones A.M.K.P. Taylor	EPSRC EEC ONR BritGas
Leeds	Flame propagation in bomb with mist, ignition delay, and soot workshop	C.G.W. Sheppard	EPSRC EEC Jaguar
Rolls-Royce	Staged combustor with radial flow, swirl-stabilized primary zone	D. Pratley D. Owen	ICR

Table 4. Diesel S&T on the Continent, Investigators, Thrusts and Sponsors.

GROUP	THRUST	INVESTIGATOR	SPONSOR
Athens	Simulation of ship and diesel dynamics, transient NOx, owner	N. Kyrtatos	Greece NATO MAN
AVL	Consulting, design, testing for large engines, Laser scattering to diagnose soot in thru-flow bomb	S. Dexter H. Fuchs	MAN IDEAS FVV
Naples	LII and rapid sampling for soot from spray injection in thru-flow bomb, cooperate with Inst. Motor	A. Caviliere L. Ragucci	CNR(ITALY) IDEAS JOULE
RWTH (LAT)	Center for automotive R&D, 20 engine test cells, LEM for soot in thru-flow bomb	F. Pischinger H. Backer	ENGINE MFG IDEAS FVV DFG
RWTH (MECH)	VW in-cylinder combustion with CV laser lighting, flamelet models, CFD, spray impulse theory	N. Peters	IDEAS VW
Wartsila	Manufacturing, large engine R&D lab, high compression, delay injection faster burn, water injection, SCR	G. Hellen	Internal

Table 5. Gas Turbine and Combustion S&T on the Continent, Investigators, Thrusts and Sponsors.

GROUP	THRUST	INVESTIGATOR	SPONSOR
DCN (PARIS)	Environmental POC for French Navy, NATO SWG-12, ICR interface for tests	Capt. J. Hartweg	NAVY
Erlangen (LSTM)	PDA spray diagnostics, combustion in porous media pulsing flow, multi-hole injection	Prof. F. Durst Dr. A. Melling	FVV
Heidelberg (IWR)	Computational combustion chemistry reduced order models, pdf techniques	Prof. J. Warnatz	EC BRITE
Munich (TECH UNIV)	Hydrogen/air flame propagation, H_2 diesel, sprays, supersonic combustion	Prof. F. Mayinger Dr. H. Ardey	BAVARIA
Rouen (CORIA)	LDA, PIV, PDA, LIF, tomography techniques. Flamelets, soot models air-assisted atomization, turbulent flame propagation.	Prof. R. Borghi	CNRS(FRANCE) EC IDEA BRITE SEP
Zaragoza	Two-phase spray properties, turbulent mixing, vortex motions, CFD, combustion lab for utilities	Prof. C. Dopazo	EC BRITE* CNRS(SPAIN)

* Program Coordinator

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